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by W. E. Moeckel
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TECHNICAL PAPER proposed for presentation at Third Annual Meeting and Technical Display sponsored by the American Institute of Aeronautics and Astronautics Boston, Massachusetts, November 29 - December 2, 1966

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION · WASHINGTON, D.C. · 1966

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INTRODUCTION

Before I discuss the current performance of electric thrustors, I would like to present some thoughts on the broader subject of this panel, namely, the future of electric propulsion. In evaluating the future of a new system, one may ask whether something can be learned from the development history of older successful systems. Let us consider, as an example, the development of the automobile. Although there are many obvious differences between the way things were done in those days, as compared to these days, there may also be some instructive similarities.

One of the well-documented facts regarding the history of the automobile is that early owners and advocates were frequently taunted with the cry, "Get a horse!" This advice was particularly heard when, as often happened, there was a malfunction of the system (e.g., stuck in the mud) or of one of its subsystems (e.g., a flat tire). There was at that time an existing system (horse and buggy) which was generally satisfactory for the missions for which it was designed, and had built up a very high reliability factor. Its fuel and propulsion system were reasonably inexpensive, and all subsystems had long shelf life, low maintenance cost, and were easily replaceable. Naturally, few mission planners at that time were willing to plan on using a new, more complex, system which was far from the mission hardware stage. In the language of our own time, we can express the viewpoint of the prospective user as follows:

"I realize that the automobile, if it ever reaches full development, has greater potential speed and range than the horse and buggy, but I don't really need all that for my contemplated applications. I can go as far and as fast as I want to go with current systems, or with simple modifications thereof. For short-range missions, we have horse-drawn vehicles, and for long-range missions we have trains and ships. I really don't see any great need for automobiles, at least not for the next decade or so. In fact, if you really want my opinion, I don't think they'll ever be used except maybe for sport or kicks. Think of the tremendous development cost involved in making the automobile into a useful, reliable system. Why, the cost of building the new streets and roads needed to utilize their potential speed would in itself ruin the country!"

The above is quite a sound and realistic appraisal of the future of the automobile at that time. So, one may ask, how did the automobile ever get developed? Actually, it was a very inefficient process. A number of unrealistic people, some of whom were in the buggy business, figured that maybe someday, not too far in the future, a lot of people might want automobiles, for one reason or another, and would stop buying buggies. Consequently, a large number of small new companies, in addition to the more adventurous established firms, began to make automobiles. They were made in many shapes and sizes, and powered by several varieties of motors. (The "all-up" philosophy of testing was in vogue at that time.) This buildup of prototypes was further stimulated by an increasing demand from people who wanted them for fun, sport, or prestige. The development phase became extremely competitive, and only a few companies eventually remained in the business. The early demand was over-estimated and the economical production methods needed to expand the market were not yet developed. Later, as the performance of the system began to approach (and even exceed) that assumed by the early enthusiasts, and as cost-reduction procedures were instituted, the demand increased exponentially, to the extent that the earlier competitive system (horse and buggy) was largely replaced, even for the limited missions for which it was originally designed and used. The moral of this, and many similar technological stories, is as follows: The most realistic people freqently turn out to be the least realistic people.

It is entertaining to speculate on the following question: If one or more government agencies had been responsible in those days for foreseeing the needs of the country with regard to ground transportation, would automobiles have been developed faster or slower than they actually were, and with greater or less ultimate cost. Of course, we must assume that the agencies in question had the same enlightened outlook on advanced technology that similar agencies have today. I would guess that, after a tremendous amount of discussion of pros and cons, at all technical and management levels, among numerous advisory committees, in the pertinent committees of Congress, and in the Executive Offices, a decision would have been made to go ahead and develop the automobile, and that it would then have been developed more rapidly and more efficiently than it actually was.

Such speculations are usually futile, and the recourse to history in predicting the future has many pitfalls. There is one lesson, however, that we proponents of electric propulsion can learn. When anyone taunts us with the advice "Use a chemical rocket!" we can adopt the quiet, superior smile of one who knows that history is on his side. Or, if that is not satisfaction enough, I am sure that a host of appropriate rejoinders will immediately come to mind.

THRUSTOR PERFORMANCE

Turning now to the more limited subject of the status of electric thrustors, let us examine the current overall efficiency of the more promising thrustor types as function of specific impulse (fig. 1). That well-tested workhorse (or should I

say work car), the Kaufman-type electron bombardment ion thrustor is still out in front, both with regards to overall efficiency and operating lifetime. Both the cesium and the mercury propellant versions of this thrustor have attained continuous operating lifetimes of more than half a year, which is almost enough for some interplanetary missions. Further improvements in efficiency and lifetime are likely.

Coming up rapidly with respect to efficiency are the MPD (magnetic plasma dynamic) arc thrustors. These thrustors, because of their simplicity, relatively high thrust density, and low operating voltage are potentially competitors of the ion thrustors, particularly for use with high-current, low-voltage power systems such as photovoltaic or the thermionic. As yet, however, operating lifetimes are quite short. Also power loss to produce the magnetic field is quite high. This power loss is not included in the efficiencies shown in figure 1. Both of these deficiencies however, can be substantially reduced with further work. Whether the overall efficiency and lifetime will reach or exceed those of the ion thrustor remains to be seen. Pulsed MPD thrustors (plasma guns) are also beginning to show efficiencies comparable to the steady-flow ones, but many rather difficult operational and systems problems remain.

In the lower range of specific impulses (800 - 2000 seconds), the electrothermal thrustors (resistojets and thermal arc jets) are still dominant. The resistojet is the first of the family of electric thrustors to find actual application in space missions. An early version has been used on an Air Force satellite, and another flight version is being developed for auxiliary use on NASA Advanced Technology satellites. Interest in the arc jet, on the other hand, has declined, because there seems to be no really suitable mission for its range of specific impulse and efficiency. One could say, of course, that the MPD arc is a felicitous marriage of work on the thermal arc jet with that on certain plasma thrustors, and therefore that the arc jet has really transcended its previous limitations. This is another example of the fact that surprisingly little of the research directed toward advanced technologies is really wasted. The knowledge and experience gained is often applicable elsewhere, and may produce really valuable advances in uexpected directions.

A former heavy favorite in the electric thrustor race, the ion accelerator using cesium-tungsten contact ionization, has faltered somewhat, and is being worked on only for possible satellite-control applications, where it must compete with a number of other systems such as the resistojet and electron-bombardment ion thrustor. The reason for the decline of this favorite is that it proved to be very difficult to get the required long operating lifetime at the high current densities needed for high efficiency with this thrustor. At lower current densities, however, (and lower efficiencies), the durability seems quite satisfactory. The primary source of inefficiency in the cesium-tungsten thrustor is the power radiated away by the hot tungsten ionizer. If this power could be supplied directly as heat (rather than electric power) from a high-temperature ($\gtrsim 1500^{\circ}$ K) nuclear reactor, or possibly a radioisotope source, a large improvement in efficiency at moderate current density would result, and interest in this early favorite would again increase. This is a particularly interesting possibility for the high-temperature reactors needed to make advanced power systems (such as nuclear thermionics and MHD) really attractive.

Many other makes and models of electric thrustor that were proposed, and received support, in the early hectic years of the space program have been either quietly abandoned, or have been directed toward purposes other than producing thrust. These include travelling-wave plasma accelerators, pulsed plasma ejectors of many species, radio-frequency heated plasmas, and several ion accelerators using relatively unsuitable ion sources. Some of these are still under study because of their intrinsic plasma physics interest, and some may well be resurrected for future specialized thrustor applications which are not now contemplated.

Although much of the early work on electric thrustors was hastily conceived, and its urgency was oversold, the net result of the artificially-induced demand was an enthusiasm and competitive spirit which at least enhanced the fun of working in the field. The practical value of such a forced-draft approach to a new technology, relative to a more methodical approach, is difficult to evaluate. In one sense, it is inefficient, in that much more money and effort is spent in the early stages than is warranted by a realistic (conservative) appraisal of future needs. But, on the other hand, it rapidly clarifies the relative value of a large number of alternative approaches, many of which would appear much later in the more methodical approach and would require evaluation at that time. It also attracts many good people into the field, some of whom produce good ideas and approaches which might not otherwise appear at all. I therefore lean toward the viewpoint that overstimulation of interest in the initial phase of development of advanced systems is ultimately more efficient and produces better results than a more methodically planned and executed program. The rigidly methodical approach should be restricted to later, more expensive, phases of development. This philosophy of research and development is quite prevalent now, and does not really need as much defense as it once did.

Future Programs and Prospects

The preceding discussion contains examples of the fact that the relative usefulness of electric thrustors is very dependent on the type of power generation system with which it will be used. An advantage in thrustor efficiency, for example may not be enough, if the required power conditioning weight or power loss is large. For major mission applications, where propulsion system mass and propellant mass are major portions of the total mass, the specific thrust of the entire propulsion system (thrust per unit mass) is the really significant parameter that should be maximized over the required specific impulse range. Nevertheless, since the way in which the subsystems will be combined will vary according to mission and development status, it is useful to define performance goals separately for each major subsystem. For this purpose, the goal of electric thrustor research can be stated as follows: to provide an envelope curve of efficiency versus specific impulse which lies above 0.8 (fig. 1) over the entire range of specific impulse from 800 seconds to 20,000 seconds. These efficiencies should include any power-conditioning

losses or auxiliary power requirements such as electromagnet power, and should be attained with operating lifetimes in excess of one year and specific weight less than one kilogram per kilowatt. Ideally, this performance should be achievable with a single thrustor operating at constant power with easy and independent control of thrust and specific inpulse (or mass flow and jet velocity). Less ideal, but still quite acceptable, would be use of two or three thrustor types to cover this wide range of specific impulse. With such thrustor capability, all mission applications presently contemplated for electric propulsion could be undertaken as soon as suitable space power systems become available, with only small penalties attributable to the thrustor subsystem. Many new ideas will be needed to approach this goal, and it will not be achieved easily. It may even take as long as the development of equally-ideal power generation systems.

Recent interplanetary mission studies, at JPL, Lewis, and elsewhere, have shown that it is not necessary to wait for these ideal thrustors and power systems in order to produce very significant improvements in mission capability. Use of well-balanced combinations of chemical and electric rockets having weights and performance now attainable can produce sizeable improvements in payload and data-transmission ability for unmanned missions to Mars, Venus, Jupiter, and near approaches to the Sun. As both thrustors and power generation systems improve, more and more advantageous applications will appear, so that a steady development toward better performance and wider usage becomes possible.

I believe that this steady development is not only possible, but extremely probable, because man, being a rather nosy animal, does not often pass up an opportunity to extend the range and scope of his exploration into the unknown. The only real hazard to the future of electric propulsion is the rather remote possibility that controlled thermonuclear fusion or gaseous fission reactors will become realities much sooner than we now think they will.

More specifically, in the area of thrustor development, the future NASA program includes: (a) further improvement in efficiency and operating lifetime of electron bombardment ion thrustors, (b) long-duration satellite flight test (by 1968) of an electron bombardment ion thrustor, (c) investigation of the performance of a large module ($1\frac{1}{2}$ meter diameter) electron bombardment ion thrustor, (d) investigation of other ion and plasma thrustor concepts that hold promise of exceeding the performance of bombardment ion thrustor in some significant manner, and (e) studies of application of ion, plasma, and electrothermal thrustors to NASA missions.

In the area of power generation, the development of large solar photovoltaic cell arrays for other applications will directly benefit electric propulsion. Arrays in the range of 5 kW to 20 kW can be used, with appropriate thrustors, to increase the capability of solar and planetary probe vehicles launched by vehicles of the size of the Atlas/Centaur and Atlas/Agena. It seems likely that this combination of moderate-sized launch vehicles and solar-electric propulsion will be a relatively inexpensive way to conduct those probe missions, as soon as suitable solar cell arrays and thrustors are available. For the much higher power levels needed for manned interplanetary missions, a continuation of present advanced technology programs on Rankine-cycle nuclear turbo-electric systems and nuclear thermionic systems should lead to development of one or two suitable systems during the next decade.

In short, the future of electric propulsion looks good, if one takes the patient, long-range point of view, and if one is not too "realistic" about it.

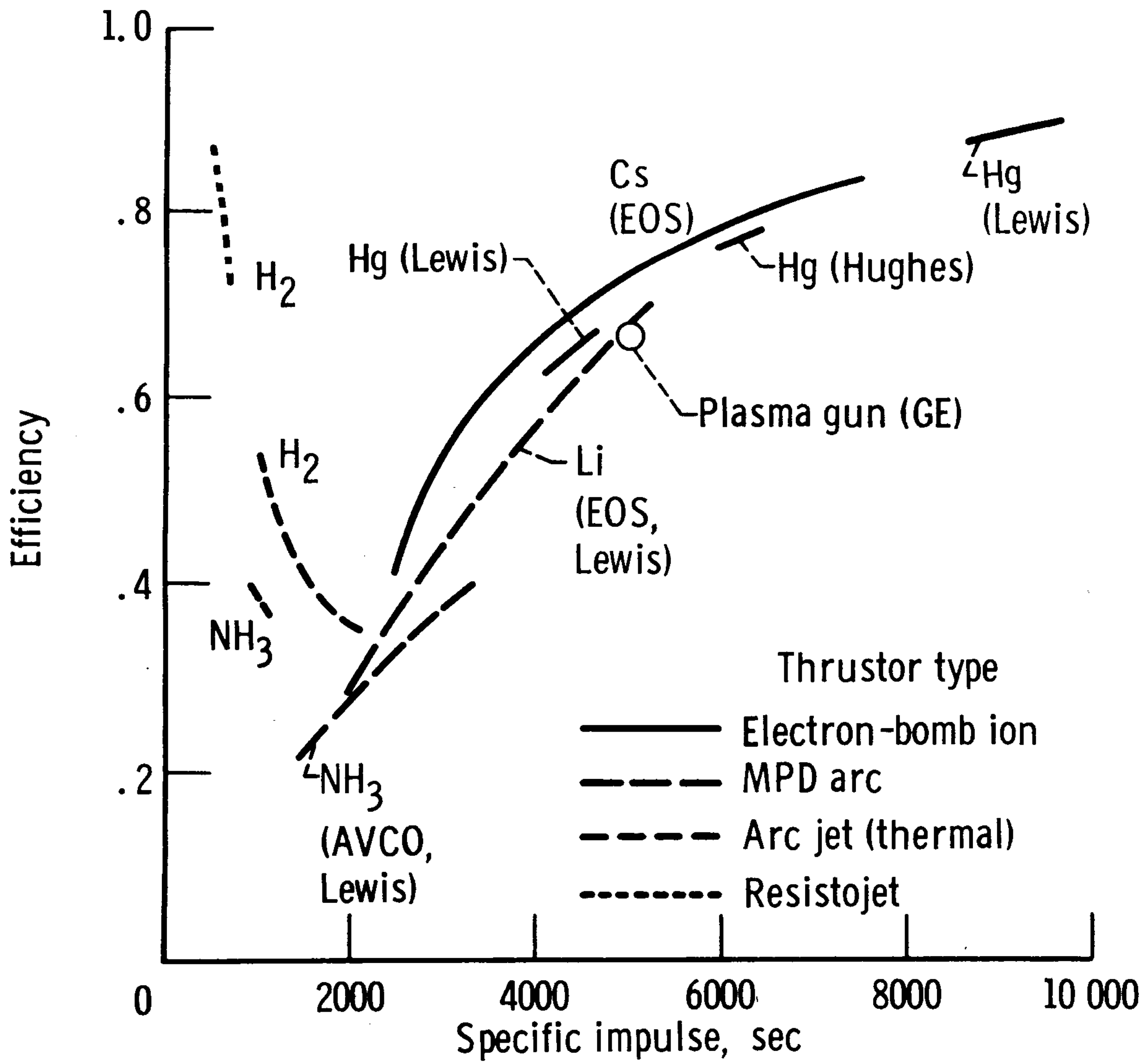

Figure 1. - Electric thrustor efficiency (no power conditioning or magnet losses).